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Controlling the Radiation Pattern of Patch Antenna Using Switchable EBG

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Abstract

The advantages of the beam steering technique are the reduction of interference, save power and to maximize connectivity for point to multi points. Antenna gain degradation is a big problem in the beam steering technique. A new antenna structure is formed by combining the concept of mushroom-like EBG structure with the switching diode to produce the radation pattern control. All sides of the patch antenna are surrounded by several cells for EBG structure. In both of the the left and right sides, through a switching pin diode, the ground plane is attached to vias. The band-stop and band-pass properties of the EBG sector can be changed with the help of switching the diode between ON and OFF state, thus yielding the beam steering into that particular sector. At 6 GHz operational frequency, this structure has the ability to steer 40º (from -20º to +20º) while minimal diodes are utilized, directivity of 10 dBi, gain 9.86 dB and the efficiency is 96.5%. This approach is robust to gain degradation and the main lobe gain is approximately constant for all steering angles.

Keywords: *mushroom-like EBG, steering antennas, switchable EBG, E-plane radiation patterns control, electromagnetic band-gap (EBG)*

1. Introduction

Microstrip patch antennas have been used widely in various applications due to low profile, low cost, light-weight and convenient integration with RF devices. Such microstrip antennas have an inherent problem of surface wave excitation. The mushroom-like EBG surface as describe in [1] and other description of the uni-planar EBG surface is shown in [2] was utilized for surrounding a microstrip patch antenna to reduce the impact of the surface waves and an improvement in the performance of antenna [3-11]. An important property of surface wave suppression supports to develop performance of antenna, like enhancing the gain of the antenna [12,13], decreasing the back radiations [14] and reduction in antenna size [15]. With the beam steering facility, these antennas are intelligent and are more efficient as this capability improves their range and capacity of the channel while reducing the interference.

The space systems and military are two most important utilizers of such antennas. The compact patch antennas with lesser complexity and greater beam steering capability can be achieved by advanced techniques of antenna fabrication. The antenna design field has been directly and positively affected by recent developments in wireless communication. There are always questions about benefits, applications and trade-offs when some new features are added to existing antennas. With the ability to work with number of systems, the reconfigurable antennas are attractive alternate to conventional ones in the modern wireless communication system.

The radio frequency (RF) switches, which are integrated in antenna, are utilized to change the structure of the reconfigurable antenna [16]. A reconfigurable antenna may exhibit varying frequency, varying radiation pattern, a variation in polarization behavior or any combination depicting any of these parameter variants [17]. The beam steering antenna has the capability to steer the beam pattern in many directions as desired by the system. This great ability of reconfigurable antennas made the wireless communication researchers to investigate further the applications of this antenna in the cellular systems, smart weaponary protection

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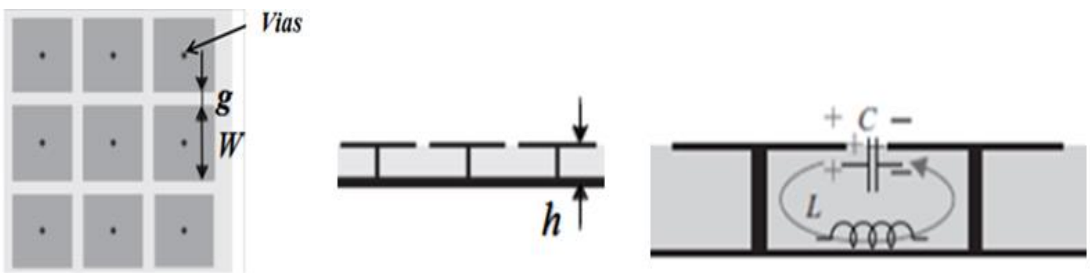
system and point to point propagation. Due to immense research in this area, several techniques have been introduced for the achievement of the beam steering through azimuth plane. One such method is the use of EBG structures [18-20]. Meta-material and electromagnetic surface design and development have contributed towards the evolvement of surface wave antenna which had effectively reduced the overall antenna size with improvements in the overall performance. Various designs and shapes of EBG structures have been implemented on the metal surfaces of dielectric substrates in order to stop and propagate the surface wave [21]. The artificially periodic structure of EBGs allowed them to behave like a band-stop thus not allowing any EM waves to propagate. Therefore, one can achieve the beam steering characteristic of EBG structure by controlling their transmission characteristics using switching devices.

In this paper, the low profile surface wave beam steering antenna is designed and analyzed. The design is based on the surrounding of EBG structure to the rectangular patch antenna for suppressing the surface waves on the high dielectric constant substrate without sacrificing any of necessary features, like the bandwidth and small size with improvement for gain, directivity and efficiency. The 6 GHz band EBG structure with switched pass-band/stop-band characteristics band gap has been designed. A beam steering antenna using the switched diode with EBG surface is presented. A low profile antenna is integrated with mushroom-like EBG in which, by switching the pin vias in and out of the two left and right sectors in E plain, the band-pass and band-stop characteristics are changed. The square EBG elements are arranged around the patch antenna and the pin vias on each sector of the EBG are switched in and out by using diode at the ground plane for connecting all the Pin vias of EBG elements to the ground plane or remove all of these pin vias from the ground plane of antenna to steer the beam into desired sector.

2. EBG Structure and Design

The EBG structure which is mushroom-like, really a 2-D EBG surface, was primarily suggested by [1]. There were four main parts in the suggested model: i) ground plane, ii) dielectric substrate, iii) metallic patches, iv) linking vias. A clear feature of stopband was showed by these EBG structures for surface-wave propagation. An LC filter array can be used for the clarification of the operation mechanism of the EBG structure. Figure 1(c) exhibits this phenomenon. The current, which is flowing through vias, causes the influence of the inductor L, while the gap between the neighboring patches caused in the impact of the capacitor C. [22] described a formula to estimate the values of *L* and *C* for such structure, as shown in Figure 1(a). Width of the patch is *W*, width of gap is *g*, the thickness of substrate is h and ϵ_r is dielectric constant:



(a) Top View (b) Cross View (c) Lumped LC

Figure 1. Geometries of mushroom like EBG a). Top view of structure, b). Cross view of structure c). Lumped LC typical for EBG analysis (1)

$$L = \mu_o h \quad (1)$$

$$c = \frac{W\varepsilon_o(1+\varepsilon_r)}{\pi}\cosh^{-1}\left(\frac{2W+g}{g}\right) \quad (2)$$

Where μ_o and ϵ_o are the permeability and permittivity of the free space respectively. Likewise we can calculate the frequency band gap as formula below:

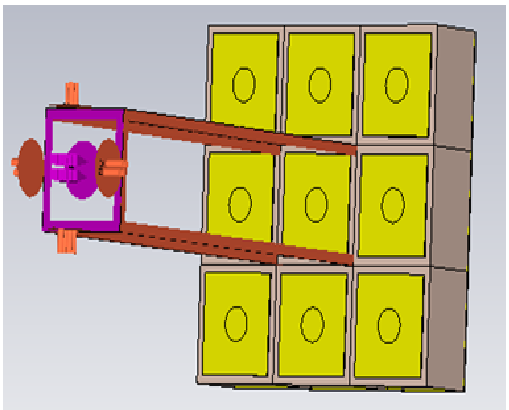
$$W = \frac{1}{\sqrt{LC}} \tag{3}$$

$$BW = \frac{\Delta W}{W} = \frac{1}{\eta}\sqrt{\frac{L}{C}} \tag{4}$$

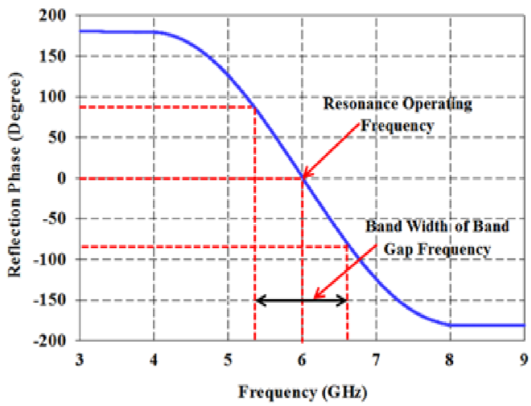
Where η is free space impedance which is 120π (377 ohms). As shown by [23], EBG structure operation can be designed by an equivalent LC filter circuit model if periodicity of structure is as small as possible in comparison with the wavelength of operating frequency. At the resonant frequency, the structure impedance is very high, and hence the emission of surface waves has been avoided by the structure. This results in the frequency band gap [1]. To demonstrate the working of EBG at 6 GHz, CST software has been used to tune the values of W and g. Figure 2(a) demonstrate the unit cell of the mushroom-like EBG structure with W=3mm ($0.06\lambda_o$), g=0.3 mm ($0.006\lambda_o$) and via diameter of 1 mm ($0.02\lambda_o$) connected between the ground plane and patch on a Rogers RT/Duroid 6010 substrate of height h=2 mm ($0.04\lambda_o$), relative permittivity of 10.2.

The working EBG band width defines as the frequency range within which the "reflection phase changes from -90^o to +90^o as shown in Figure 2(b). As the frequency progresses, the characteristic of the reflection phase changes from +180^o to -180^o. The characteristics of the reflection phase for this structure are just same as PEC surface at higher and lower frequency regions. At the resonant frequency (i.e. 6 GHz), the EBG shows artificial magnetic conductor (AMC) property between +90^o to -90^o region and has zero degree of reflection phase [24].

The design proposed in the current study is exhibiting high impedance at 6GHz. The key idea of this research is to suitably design the patch size such that the antenna resonant frequency drops within the EBG band gap and then the surface waves could be prohibited. The band gaps of 3mm ($0.06\lambda_o$) patches are suitable for the side lobe and back radiation reductions, where the antenna frequency drops inside the range area of EBG band gap. In other way, we can state that the EBG band gap can cover the resonance frequency of this designed antenna.



(a)



(b)

Figure 2. (a) EBG unit cell and (b) Reflection phase for the EBG unit cell

3. Antenna Design with EBG and Pin Diode

Patch antenna, widely known as microstrip patch antenna, a lot of research has been done by the other investigators to make it usable with a small size. Patch antennas are available in different shapes and sizes. Rectangular patch is most simple one and its fabrication is easy. The antenna size is decreased as the substrate relative dielectric constant is increased [25]. In this research, we designed a rectangular patch antenna with probe feed on the Rogers RT/ Duroid 6010, the thickness of the substrate is h=2.2mm (0.044λ_o) and its dielectric constant is ϵ_r=10.2. The lengths of the patch are 6.1 mm (0.124λ_o) by 7.4 mm (0.148λ_o). By surrounding the rectangular patch antenna with 4 columns and each of the left and right sides are composed of twenty-eight square-patches mushroom EBG unit cell or four columns of EBGs shifted inwards to antenna edges by 0.3mm (0.06λ_o) equal to gap of its design. Structures of EBG were sited more than two periods away from the patch antenna edges. The interconnecting microstrip lines limit the arrangement of EBG structure in periodic manner. The mushroom-like EBG structures have inherent benefit that they don't have such lines, thus overcoming the limitation. Using this feature, as shown in Figure 3 the structures of EBG have been shifted inwards to the antenna ends with general size is 49.2mm (0.98 λ_o)×52mm (1.04λ_o).

We successfully achieved the antenna improvement by suppressing the surface waves at this design. We used a switching pin diode to connect the centers of the EBG square patches to the ground plane as shown in Figure 4, where we make a slot of 0.3 mm on the ground plane of antenna which surrounded all of the EBG patches with pin vias for the left and right sides of antenna. The structure of EBG has been designed for 6 GHz band-stop when the diode is in ON state that is EBG pin vias are directly connected with the ground plane. When the diode is in OFF state, which means the EBG pin vias and ground plane are not connected, a pass-band around the same frequency band (6 GHz) is created. The number of diodes in either of the two sectors (left and right) is reduced to one, thus we have a total of 2 diodes. This is due to slot in the ground of each sector. This design reduced the effect of the biasing circuit on the antenna characteristics. The antenna pattern directivity has been controlled by connecting and disconnecting vias in each sector to vary the beam direction and gain. Simulation results were presented in the next section.

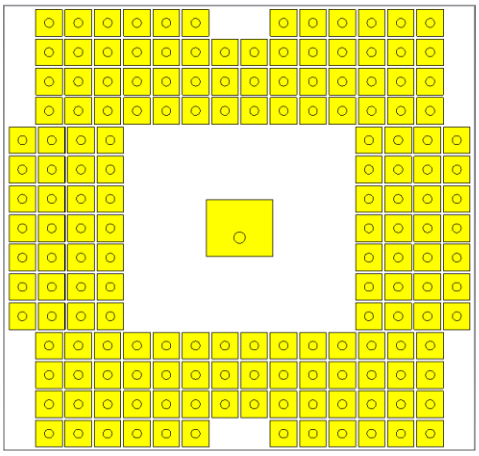


Figure 3. A rectangular patch antenna surrounded by mushroom-like EBG structures

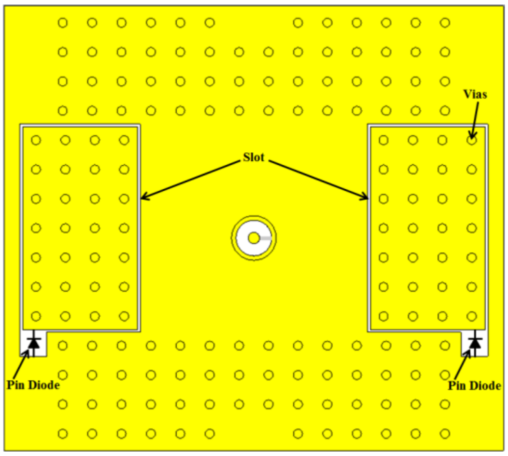


Figure 4. Back view (ground plane) of a rectangular patch antenna surrounded by mushroom-like EBG structures with two switches (pin diode)

4. Results and Analysis

In the previous section, we have presented the design and modeling parameters of rectangular patch antenna in 6GHz band which are surrounded by the EBG with the Band gap. Simulations were done for the surrounding antenna by EBG and the original rectangular patch antenna in order to compare the performance. The first case as shown in Figure 4, is when the two diodes (at the left and right sides) are ON (short circuit) for showing the suppressing surface waves and its effects on antenna improvement in terms of gain, directivity and efficiency of antenna. It is observed that when using four columns at left and right sides with shifting inwards to the antenna ends by 0.3 mm (0.06λ_o) as shown in Figure 3. The simulated S-parameters in terms of S-11 shows good matching S-11 at 6 GHz. The configurations slightly shifted the resonant frequency of the antenna to 5.99 GHz when using EBG with good matching S-11 of less than -31dB, while the resonance frequency for the antenna without using EBG pointed at 6.01 GHz with matching S-11 of less than -20 dB as shown in Figure 5.

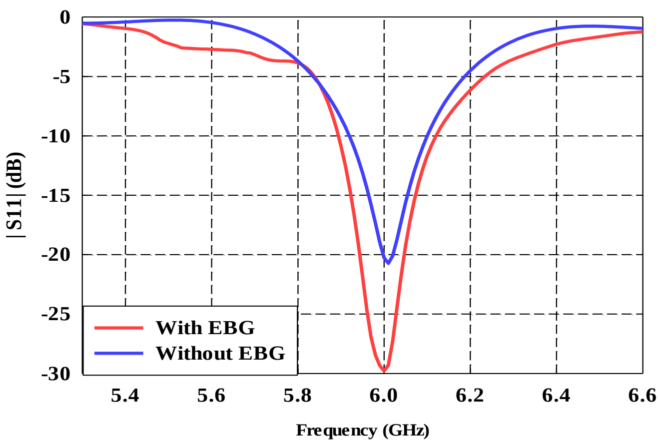


Figure 5. Return loss of the microstrip antennas with EBG structures and without EBG structures

First case when the two of the diodes have been switched ON as shown in Figure 4, the stop band will appear for all antenna borders. For the purpose of a comparison, the antenna (improved by EBG structures) was adjusted at resonant frequency of 6 GHz, and was compared with rectangular patch antenna without EBG structures. The usual rectangular patch antenna (without EBG) has -7 dB side lobes. This side lobe will reduce the antenna gain. Additionally, the width of the main lobe was around 87.3°.

The directivity of the antenna could be reduced by such big aperture angle. The radiation properties of the electric field of the newly proposed antenna (with EBG structures) observed a better reduction in the side lobe level around -17.5 dB. Further, the beam width has been found to be just above 57° due to the suppressing surface waves at stop band of the EBG. These features generated a better directivity in the direction of broadside of the antenna and improved gain as compared to the original rectangular patch antenna (without EBG). The measured directivity of this patch antenna (with EBG elements) is found to be 10 dBi and the gain is 9.86 dB at 0° main lobe direction while the directivity and gain of the usual patch antenna (without EBG) are 5.66 dBi and 4.74 dB as shown in Figure 6(a) and 6(b).

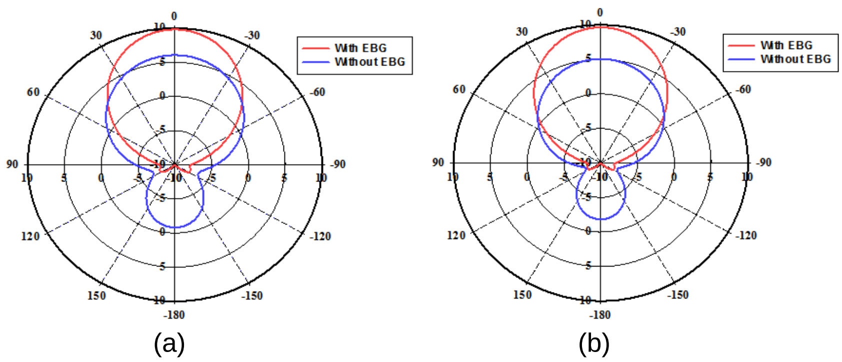
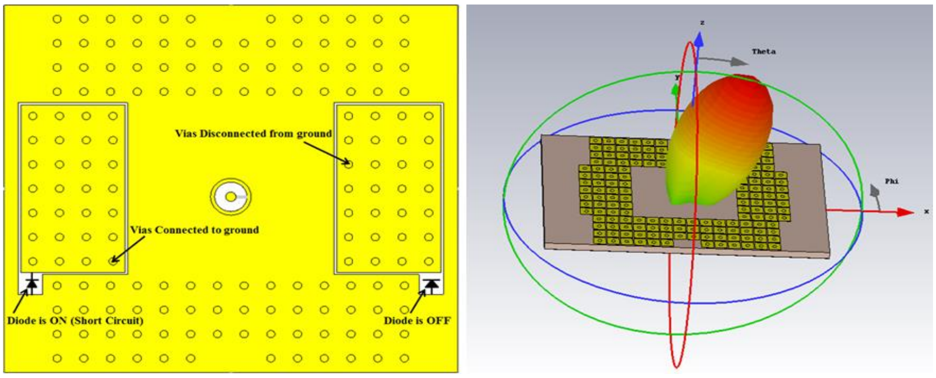


Figure 6. First Case (two diodes switched ON), improvement of antenna when connecting pin vias for both right and left sides (a) Directivity with and without EBG at 0° main lobe direction (b) Gain with and without EBG at 0° main lobe direction

Second case when the diode on the left side of antenna has been switched ON (short circuit) and at the same time the diode on the right side was switched OFF (open circuit) as shown in Figure 7(a), the stop band is appearing on the left side and the pass band is appearing at the right side of antenna. The simulated power pattern of the antenna with EBG is directed from the stop band side of antenna (left of antenna, where the diode is ON state) to the pass band side of antenna (right of antenna, where the diode is in OFF state) in the direction of $+20^o$ as shown in Figure 7(b).



(a) (b)

Figure 7. Second Case (a) Diode is ON state in the left side and OFF state in right side of the antenna, (b) Radiation Pattern is directed from the left side (connecting Vias to ground plane) to the direction of $+20^o$ (disconnecting Vias from the ground plane)

The mushroom-like EBG has been simulated to explain its capability to control the power pattern directivity around the elevation plane (E-plane) of microstrip patch antenna. This has been achieved by arranging in each of the left and right sides twenty-eight square-patches mushroom EBG unit cell or four columns of EBGs shifted inwards to antenna edges by 0.3mm ($0.06\lambda_o$). By alternately switching the diodes, the EBG sector surface characteristic will also be changed. Pin vias have been switched IN (connected) and OUT (disconnected) at each sector to control the beam direction. For this case, to direct the pattern towards the right sector, pin vias at the sector have been switched OFF, whereas pin vias have been switched ON for the left sector. As a result, the surface wave has propagated towards right sector (pass band) and reflected from the left sector. Figure 8 shows the Theta-plane power pattern at phi=0°, which is directed towards the right sector at theta=+20° with the maximum gain and directivity which equal to 9.4 dB and 9.7 dBi respectively.

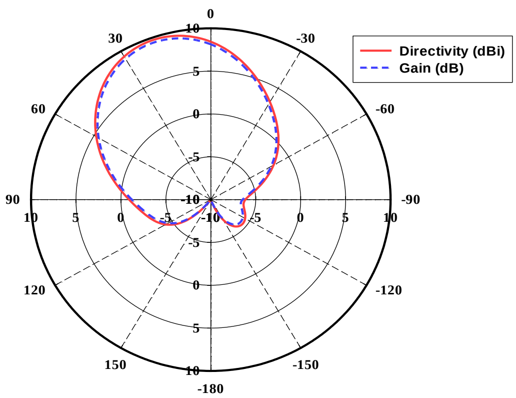
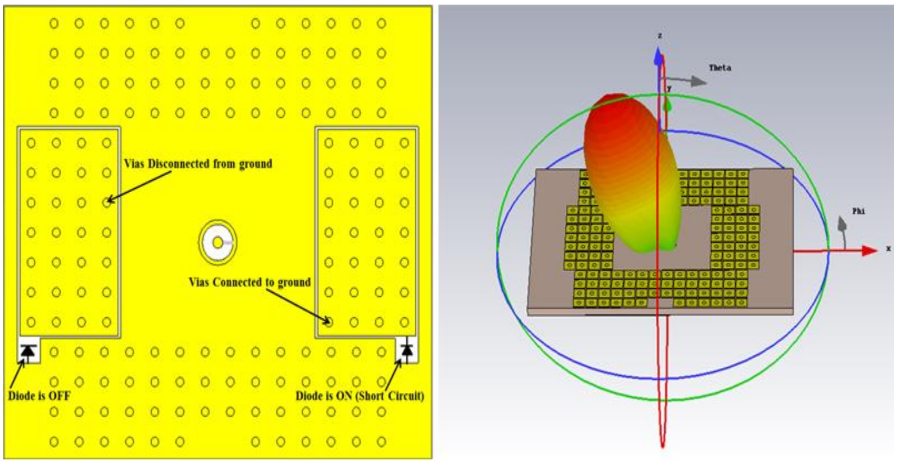


Figure 8. Power patterns in the elevation plane for second case (connecting pin vias in the left side and disconnecting from the right side) at theta=+20°

Third case when the diode on the right side of antenna has been switched ON (short circuit) and the diode on the left side was switched OFF (open circuit) as shown in Figure 9(a), the stop band will appear on the right side and the pass band will present at the left side of antenna. The simulated power pattern of the antenna with EBG is directed from the right side of antenna (stop band) where the diode is ON state to the left side (pass band) where the diode is OFF in the direction of -20^{o} as shown in Figure 9(b).



(a) (b)

Figure 9. Third case (a) Diode is ON state in the right side and OFF state in left side of the antenna, (b) Radiation Pattern is directed from the right side (connecting Vias to the ground plane) to the direction of -20^{o} (disconnecting Vias from the ground plane)

Same arrangement method of EBGs for the previous case to clarify its capability to control the power pattern directivity around the elevation plane (E-plane) of the microstrip patch antenna. by alternately switching diode the EBG sector surface characteristic will also change. To direct the pattern towards the left sector, pin vias at the sector have been switched OFF (disconnected from the ground plane), whereas pin vias have been switched ON (connected to ground plane) for the right sector. As a result, the surface wave has propagated towards left sector (pass band) and reflected from the right sector. Figure 10 shows the Theta-plane power pattern at phi=0°, which is directed towards the left sector at theta=-20° with the maximum gain and directivity. This is equal to the previous case, i.e. 9.4 dB and 9.7 dBi respectively. This approach does not suffer from gain degradation and the main lobe gain and directivity are approximately constant for all steering angles.

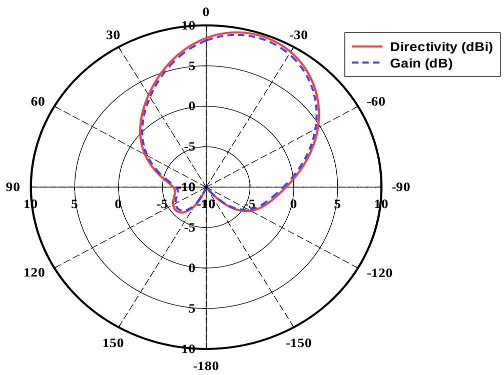


Figure 10. Power patterns in the elevation plane for third case (connecting pin in the right side and disconnecting from the left side) at theta=-20°

A surface wave influence in power pattern is often considered as unfriendly, since it decrease the antenna efficiency by increasing the side lobe. By increasing the substrate thickness to avoid the narrow band width due to the high dielectric constant, the surface waves will also increase. This problem can be solved by using EBG with connecting pin vias between the ground and the patch of antenna (short circuit) for suppressing surface waves. Figure 11, shows the improvement in the antenna efficiency for all cases when the rectangular antenna is surrounded by EBG structures. Antenna without EBG has efficiency equal to 80% and after applying the EBG with the same antenna, in first case where the two switches diode has been chosen ON stat (short circuit) we achieved the better improvement in 0° main lobe direction, the efficiency become 96.5%. For the second and third case, when the diode on the one side of antenna has been switched ON (short circuit) and at the diode on the other side was switched OFF (open circuit), same improvement has been achieved in +20° and -20° main lobe direction and the efficiency was observed to be 95%.

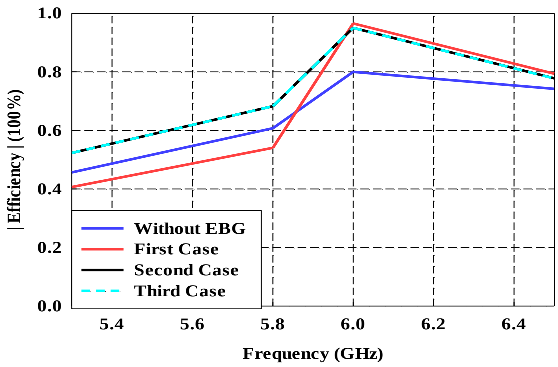


Figure 11. Efficiency improvement by using EBG

5. Conclusion

We have presented a new antenna structure that is formed by combining the concept of the mushroom-like EBG structure for suppressing the surface waves with the switching diode to produce the beam steering technique. To achieve the required beam steering in the elevation plane, EBG of several cells surrounded the patch antenna and placed symmetrically on the two opposite sides of it. Each of the left and right sides are composed of twenty-eight square-patches mushroom EBG unit cell or four columns of EBGs shifted inwards to antenna edges by 0.3mm ($0.06\lambda_o$). A switching pin diode is used to connect the vias in both sides to the ground plane.

The band-pass and band-stop characteristics of the EBG sector can be varied by switching the diode in to ON and OFF state. This allows the steering of beam into required sector, thus increasing the directivity. The simulation results presented here shows the flexible and effective beam steering capability of EBG structures in the E plane using minimum number of pin diodes. At 6 GHz operational frequency, this design has the ability to steer the elevation to 40º (from -20º to +20º), directivity of 10 dBi, gain 9.86 dB and efficiency 96.5%. Unlike the conventional beam steering techniques, the current design approach does not have any gain degradation and the main lobe gain is approximately constant for all steering angles. To the best of our information and for the future works, there are no comprehensive outcomes stated for antenna arrays beam steering by using EBG. This structure has potential prospects in wireless and 5G cellular networks.

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